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THE ROLE OF MAGNETIC RECONNECTION PHENOMENA IN THE REVERSED-FIELD PINCH

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ABSTRACT

The reversed-field pinch (RFP), an axisymmetric toroidal magnetic confinement experiment, has physics rich in the area commonly called field line reconnection or merging. This paper reviews the topics where reconnection plays a vital role: (a) RFP formation and the phenomenon of self-reversal, (b) RFP sustainment in which the RFP configuration has been shown to be capable of maintaining itself for times much longer than earlier predictions from classical resistive MHD theory, (c) steady state current drive in which "dynamo action" and associated reconnection processes give rise to the possibility of sustaining the configuration indefinitely by means of low frequency ac modulation of the toroidal and poloidal magnetic fields, (d) the effects of reconnection on the formation and evolution of the magnetic surfaces which are intimately related to the plasma containment properties. It appears that all phases of the RFP operation are intimately related to the reconnection and field regeneration processes similar to those encountered in space and astrophysics.

1. Introduction

One of the motivations of the Chapman Conference on Reconnection was to bring physicists who study space and laboratory plasmas together allowing a fertile interchange of ideas and physics knowledge which have much in common in the two disciplines. The reversed-field pinch (RFP) has much to offer in this regard since its formation and sustainment involve the phenomenon of field-line reconnection.

The RFP stems from the earliest Z-pinches [Cousins and Ware, 1951] following the studies of Bennett, [1934]. In the 50's much research was done on the Z-pinch, particularly at laboratories in Los Alamos and Livermore in the U.S., Harwell and Aldermaston in the U.K., and Fonteray-aux-Roses in France. A good reference list for this early work is available in [Glasstone and Loveberg, 1960]. Later history and physics discussions of the toroidal pinch concept are outlined in [Baker and DiMarco, 1975], [Bodin and Keen, 1977], [Bodin and Newton, 1980] and [Baker and Quinn, 1981]. The basic pinch idea is to use the self-magnetic fields of a current plasma column to contain the plasma. The simple Z-pinch concept was plagued with problems of MHD instability and the modern RFP is the result of experimental and theor tical studies which have led to grossly stable pinch configurations.

The objectives of the paper will be to discuss specific topics in which the space physics related concepts of field line reconnection or merging, flux annihilation or generation, and dynamo action are relevant in the RFP physics. These topics include RFP formation and self-reversal, RFP sustainment, steady state current drive, and effects on field line topology which affect plasma containment.

2. The Reversed-Field Pinch Configuration

The modern day reversed-field pinch used for fusion-oriented plasma containment studies is typified by the Los Alamos ZT-40M experiment [Baker, et al.,1983] shown in Fig. 1. Currently there are four additional RFP experiments in which extensive results are available: OHTE in the U.S. [Tamano, et al., 1983], HBTX-1A in the U.K. [Bodin, et al., 1983], ETA BETA II in Italy [Antoni, et al., 1983], and TPE-1R(M) in Japan [Ogawa, et al., 1983]. There are several other RFP experiments which are recently operating or are scheduled to begin operation in 1984: the REVERSATRON at the University of Colorado; ZT-P in Los Alamos; REPUTE-I, Tokyo; STP-3, Nagoya; HIT-1, Hiroshima; STE-RFP, Kyoto; and a small experiment at the Tokyo Institute of Technology.

The modern RFP utilizes a thin, toroidal metal vacuum liner nested inside a thick highly conducting shell. The liner is resistive and the shell has gaps in the poloidal (short way around the torus) and toroidal (long way around the torus) directions to allow the pulsed fields to enter the plasma region inside the liner. In experiments using very slowly applied toroidal fields, the gap in the shell which extends in the toroidal direction can be omitted. Outside the shell are poloidal and toroidal windings which produce the necessary magnetic fields to (1) induce the toroidal electric field to drive the toroidal current that produces the poloidal confining field B_θ, (2) provide an initial toroidal stabilizing field B_ϕ, and (3) provide equilibrium controlling fields as needed during startup and sustainment. In the present experiments the windings are energized from capacitor banks. The reversed field configuration is a combination of toroidal and poloidal fields producing a set of nested surfaces whose field lines possess a high degree of shear as the fields from different magnetic flux surfaces are compared

(Fig. 2). The RFP differs from the tokamak by having the highly sheared magnetic field whose toroidal field reverses in the outer region of the discharge and by having a thick conducting shell whose purpose is to provide global MHD stability, whereas the tokamak relies on a very strong unidirectional toroidal magnetic field. A general schematic comparison of the RFP and tokamak field components along the midplane of the torus is given in Fig. 3. Magnetic cores are often used to increase the transformer coupling from the pulsed poloidal field coils (multi-turn transformer primary) and the plasma (single turn secondary).

3. Reconnection During RFP Formation

3.1. Formation by Reconnection of Large Amplitude Helical Disturbances

The earliest experiments on fast-current-rise toroidal pinches were formed inside a toroidal flux conserving shell and demonstrated the ability of a toroidal current-carrying plasma, having an initially unidirectional toroidal stabilizing field, to re-arrange itself into a pinched discharge whose toroidal field is increased internally and reversed in the outer regions of the pinch. See, for example, [Colgate, et al., 1958]. This self-reversal process, observed in the early fast pinches, (microsecond time scales) was explained qualitatively as follows. An axisymmetric toroidal pinch first forms as shown in Fig. 4a. The highly pinched plasma column is MHD unstable to a helical perturbation and kinks into a large amplitude helix as shown in Fig. 4b. This helical, multi-turn solenoid-like current generates an increased component of toroidal field, thus increasing the toroidal flux in the interior region of the plasma. Since the conducting boundary conserves the total toroidal flux on the time scales of these experiments, eddy currents are induced in the wall which produce a negative toroidal flux in the outer portion of the discharge thus maintaining a constant total toroidal flux inside the conducting shell. At this point the pinches tend to return toward axisymmetry. A closer look at the process is shown in a sector of the torus in Fig. 5. The field of the kinked plasma in Fig. 5b has helical flux surfaces and a helical x-point locus (separator). Thus the plasma can return towards axisymmetry by field line reconnection at the x-point and by a diffusion and smoothing of the plasma column. The ideal smoothed out configuration of Fig. 5c now has a reversed field where the toroidal field was initially all in the same (forward) direction (Fig. 5a). It is clear that field-line reconnection is a necessary ingredient of forming an axisymmetric pinch by self-reversal since rapid changes in field line topology and changes in the flux inside and outside separatrix surfaces are involved.

The simplified qualitative picture just described obviously involves plasma dynamics, reconnection and diffusion processes. The actual quantitative theoretical description of self-reversal is currently under intense study using powerful two and three dimensional (3-D) MHD computer codes. The earliest RFP results from 3-D numerical computations were reported by Sykes and Wesson, [1977]. They verified the growth of a helical unstable mode which produced the field reversal. As the calculation proceeded, a second helical instability appeared with half the wavelength of the first one. This was followed by resistive tearing, reconnection and a return to near axial symmetry. These first calculations used a straight linear pinch simulated in a rectangular cross-section conducting box. The calculation did verify the early concepts that self-reversal can be produced by the growth of a helical disturbance and a return to symmetry by reconnection processes. This work has been recently confirmed and extended with more powerful computer codes [Schnack, et al., 1983; Aydemir and Barnes, 1983a, 1983b; Holmes, et al., 1983]. Experimental evidence for field reversal by helical modes is summarized by Bodin and Newton [198?].

3.2. The Taylor Relaxation Model

A model which predicts that a current-carrying plasma column located inside a cylindrical (coordinates r, θ, z) flux conserving shell, with a suitably high value of the ratio of toroidal current to poloidal flux, will relax to a reversed-field configuration has been proposed [Taylor, 1974, 1975, 1976]. The basic premise in this description is that a given configuration of magnetic field having an initial value of magnetic helicity $K = \int_{vol} \underline{A} \cdot \underline{B} dV$ and longitudinal magnetic flux $\Phi = \int_A B_z dA$ will evolve by magnetic reconnection processes to a lowest state of magnetic field energy $W_B = \int_{vol} B^2 dV$ keeping the value of K and Φ constant. The use of the magnetic helicity as an invariant was used earlier in the astrophysics literature in related arguments leading to the prediction of force-free field configurations [Woltjer, (1958), (1959), (1960)]. The magnetic helicity is an exact invariant for any closed flux tube in a perfectly conducting fluid. The Taylor hypothesis is that the localized reconnection processes due to a small amount of dissipation will change the field line topology but will leave the total global magnetic helicity in the plasma volume conserved on the time scale of the relaxation, while the magnetic energy is not. This hypothesis leads to a force-free configuration satisfying $\nabla \times \underline{B} = \mu \underline{B}$ where μ is a constant. In terms of easily measured dimensionless parameters $\Theta = B_{\theta wall}/B_{zave}$ and $F = B_{zwall}/B_{zave}$ the model predicts cylindrically symmetric Bessel function solutions $B_z = B_o J_o(2\Theta r/a)$ and $B_\theta = B_o J_1(2\Theta r/a)$ for $\Theta \leq 1.55$ and a helically symmetric state for higher Θ. For $\Theta \geq 1.2$ the field is reversed. The lowest energy states lie on a locus in F-Θ space as shown in Fig. 6. In practice, the Taylor model is a qualitative guide to the RFP self-reversal behavior. Experimentally the F-Θ curve normally lies above that predicted as shown in Fig. 7. The actual experiments deviate from the idealized Taylor model in several aspects as shown in Table I. In spite of these differences the model has been a very useful guide for the states resulting from the reconnection relaxation processes.

TABLE I

DEVIATIONS FROM THE TAYLOR PROBLEM IN REAL EXPERIMENTS

Taylor	Experiment
Plasma surrounded by perfect conductor.	Double wall, closest one resistive, gaps in outer shell.
Passive relaxation.	Driven system (toroidal E field)
Zero plasma pressure.	$\beta_p = 2\mu_o\bar{P}/(B_{\theta wall})^2 \sim 10\%$
High conductivity plasma throughout the volume.	Cold plasma next to wall, gas released from the wall.

The Taylor analysis has generated much interest and many authors have studied variations and modifications of the original analysis. A correction to the original work has been published [Reiman, 1980, 1981]. Extensions of the model from cylindrical to toroidal geometry have been made [Miller and Turner 1981; Faber, White, and Wing, 1982a, 1982b; Edenstrasser, 1983a]. Arguments relating to why the magnetic helicity should decay slowly compared to the magnetic energy have been advanced [Montgomery, Turner, and Vahala, (1978)]. An extensive statistical mechanical study using incompressable MHD and the K and Φ invariants predict a state having fluctuations about the Taylor state [Turner, 1983a, 1983b]. The Taylor work has spawned many other papers which discuss minimum energy states obtained using differing constraints or geometries, some of which allow a non-zero plasma pressure and/or fluid flow: [Rosenbluth and Bussac, 1979; Sudan, 1979; Finn, Manheimer, and Ott, 1981; Marklin and Bondeson, 1980; Bondeson, et al., 1981; Erlebacher, 1981; Bhattacharjee, et al., 1980, 1982; Brandenburg, 1982; Edenstrasser and Schuurman, 1983b; Finn and Antonson, 1983; Turner, 1983c]. A related analyses which maximizes entropy instead of minimizing energy has also appeared [Hameiri and Hammer, 1982].

3.3. Toroidal Flux Generation

The generation of toroidal flux is involved in the explanation of self-reversal phenomenon of Sec. 3.1. The generation of flux has also been demonstrated clearly for a very slowly rising current (~ 14 ms risetime) in ZT-40M where, unlike the earlier experiments, the high temperature (~ 0.3 keV) and long duration current pulse (~ 15 ms) have precluded internal magnetic probe measurements. The measurement is made by means of a toroidal flux pickup loop surrounding the vacuum liner, as shown in Fig. 8. [Phillips, et al., 1983]. The measured waveforms of toroidal current, the toroidal flux, and toroidal field just outside the liner, are shown in Fig. 9. The RFP configuration is first formed by a rapid rise in the current to ~ 70 kA in 0.75 ms (startup) and then allowed to slowly increase to ~ 170 kA (see Fig. 9a). As seen in Fig. 9b and 9c, the total toroidal flux as measured by the external loop increases and the external field remains reversed during the entire slow rise of current. Since the toroidal field is negative on the outside, the positive flux Φ^+ in the discharge is surrounded by an annular region of negative flux Φ^- as shown schematically in Fig. 8. The dotted line represents the locus of the toroidal field null. Applying Faraday's law to the region inside the toroidal field null gives

$$\dot{\Phi}^+ = -\oint_{\text{null}} \underline{E}\cdot d\underline{\ell} \quad . \tag{1}$$

Similarly, for the negative flux annulus

$$\dot{\Phi}^- = \oint_{\text{null}} \underline{E}\cdot d\ell - \oint_{\text{liner}} \underline{E}\cdot d\underline{\ell} \quad . \tag{2}$$

Adding the two equations we obtain the total $\dot{\Phi}$ sensed by the flux loop

$$\text{loop voltage} = \dot{\Phi}^{+} + \dot{\Phi}^{-} = -\oint_{\text{liner}} \underset{\sim}{E} \cdot \underset{\sim}{d\ell} \quad . \tag{3}$$

When the flux is considered to move at a velocity $v_E = \underset{\sim}{E} \times \underset{\sim}{B}/B^2$ [Longmire, 1963], the first terms in the right hand sides of Eqs. (1) and (2) represent the equal annihilation or generation rates of positive and negative flux at the toroidal field null and cancel when the two equations are added. Annihilation and generation correspond to the mean poloidal $\underset{\sim}{E}$ at the reversal point being positive or negative, respectively. The remaining term [rhs of Eq. (3)] represents the rate of entering or leaving of negative flux at the liner boundary. Since the field is always reversed at the boundary for the slow rise of current in Fig. 9, the net flux can only increase by the loss of negative flux from the volume, i.e., $\oint_{\text{liner}} \underset{\sim}{E} \cdot d\ell < 0$. To demonstrate the generation of positive flux (and the equal amount of negative flux) during the slow rise of current, one must show that more negative flux is removed at the boundary than was initially present just after the RFP was formed during the startup. This demonstration follows from a theorem [Caramana and Moses, 1983a] which puts an upper limit on the ratio of negative to total flux required for equilibrium

$$\frac{|\Phi^{-}|}{\Phi_{\text{total}}} < \frac{1}{2}\left[(F^2 + \Theta)^{1/2} - 1\right] \quad , \tag{4}$$

where F and Θ are as defined in the last Section. When this upper limit is calculated for the discharge conditions after startup $F = -0.2$ and $\Theta = 1.6$ for Fig. 9 it is found that the observed 150% increase of net flux is five times the 30% limit imposed by Eq. (4) [Caramana and Baker, 1983b]. Thus flux is generated not only during the rapid startup of an RFP but also during a very slow rise of current. This interesting flux generation effect, which is the opposite of the well known field annihilation due to resistive dissipation, has been called "the dynamo effect" in analogy to the field generation by solar and terrestrial dynamos [Moffat, 1978].

4. Sustainment of the RFP Configuration

4.1. Predictions of a Simple Symmetric Ohm's Law Model

In the early history of the reversed field pinch, it was generally believed that the RFP configuration once produced would, of necessity, decay by resistive diffusion (see for example [Robinson, et al., 1972]). Indeed if a cylindrically symmetric pinch were formed and a simple Ohms law were valid

$$\underline{E} = \underline{\underline{\eta}} \cdot \underline{J} - \underline{v} \times \underline{B} \quad , \tag{5}$$

($\underline{\underline{\eta}}$ is the resistivity tensor, $\underline{J}$ the current density, and $\underline{v}$ the plasma velocity) then this conclusion would be correct. This follows from Eq. (1) when one evaluates the right hand side. Noting that $d\underline{\ell}$ lies along $\underline{B}$, which is totally poloidal at the toroidal field null, one may write

$$\oint_{null} \underline{E}\cdot d\underline{\ell} = \oint [\underline{\underline{\eta}}\cdot\underline{J} - \underline{v}\times\underline{B}]_{\parallel}\cdot d\ell = \oint \eta_{\parallel} J_{\theta} d\ell > 0 \quad , \tag{6}$$

where $\parallel$ denotes a component parallel to $\underline{B}$. The last inequality follows from the fact that $\eta_{\parallel} > 0$ for a collisional resistivity, $\mu_0 J_\theta = -\partial B_z/dr$ (from the Maxwell equation $\nabla \times \underline{B} = \mu_0 \underline{J}$) and $\partial B_z/\partial r < 0$ where $B_z = 0$ (the field reversal radius). Thus $\eta_{\parallel} J_\theta$ is positive and from Eq. (1) $\dot{\phi}^+ < 0$ and the positive flux must decay.

The interesting feature of recent experiments is that constant current RFP discharges have been obtained for lifetimes much exceeding the predictions of classical theory and Ohm's law. It now appears, from this strong experimental evidence, that the RFP configuration can be sustained as long as the current and plasma density are maintained. The flat-topped current of the present ZT-40M experiment is maintained in present experiments by a toroidal electric field produced by transformer action. The plasma density can be replenished when needed by gas injection. A sample flat-topped current discharge in ZT-40M sustained 20 ms is shown in Fig. 10. Classical local ohmic calculations for cylindrical symmetry predict that, for the conditions of this discharge, the positive toroidal flux would decay in a few milliseconds [Caramana and Baker, 1983b]. One is thus led to the conclusion that the discharge cannot be described by a symmetric local Ohm's law model.

In general, this implies, that for the sustained and slowly rising current RFP, one or both of the following: (1) the local Ohm's law description is not valid, (2) the pinch is not symmetric.

4.2. The Mean Field Theory for a Turbulent Dynamo

A popular explanation of field generation and sustainment in the RFP was first advanced by Gimlett and Watkins, [1975] borrowing from the mean-field MHD used to describe dynamo theories for the earth, sun and other conducting, rotating bodies in astrophysics. (See, for example, [Krause and Rädler, 1980].) Just as a local Ohm's law, symmetric RFP cannot exist in steady state, neither can the fields of a rotating conducting object retain steady axisymmetric field in the presence of an Ohm's law description. This conclusion is implied by a theorem due to Cowling [1934]. The essence of mean-field approach is to assume that there are mean $\langle\ \rangle$ and fluctuating δ components for $\underline{B} = \langle\underline{B}\rangle + \delta\underline{B}$ and $\underline{v} = \langle\underline{v}\rangle + \delta\underline{v}$, where $\langle\delta\underline{B}\rangle = \langle\delta\underline{v}\rangle = 0$. When these are substituted into Ohm's law Eq. (5) and the resulting equation averaged, one obtains a modified Ohm's law for the mean electric field $\underline{E}$

$$\langle\underline{E}\rangle = \langle\underline{\underline{\eta}}\cdot\underline{J}\rangle - \langle\underline{v}\rangle\times\langle\underline{B}\rangle - \langle\delta\underline{v}\times\delta\underline{B}\rangle \quad . \tag{7}$$

Taking components along the mean toroidal field null and, for simplicity, neglecting the fluctuations in resistivity

$$\langle\underline{E}\rangle_{\parallel} = \eta_{\parallel}\langle J_{\parallel}\rangle - \langle\delta\underline{v}\times\delta\underline{B}\rangle_{\parallel} \quad . \tag{8}$$

The new term in Eq. (8) need not vanish even though the mean values of the fluctuating components of plasma velocity and magnetic field $\delta\underline{v}, \delta\underline{B}$ are zero. For the simplest case of isotropic turbulence, the $\langle\delta\underline{v}\times\delta\underline{B}\rangle$ term gives a contribution $\alpha\langle\underline{B}\rangle$ to the mean electric field, and is called the "alpha effect". Studies and extensions of the alpha effect concept in the RFP context have been made [Schaffer, 1982; Gerwin and Keinigs, 1982; Keinigs, 1983]. If the correlations and amplitudes of $\delta\underline{v}$ and $\delta\underline{B}$ are suitable, the two terms on the right hand side of Eq. (8) may cancel or even have the opposite sign from that of a conventional collisional Ohm's law. Since Faraday's law is linear, the mean values of flux and electric field satisfy

Faraday's equation with no new terms. One then has a possible way around decay implied by Eqs. (1) and (6) since the mean poloidal $\underline{E}$ can now be zero or negative and the mean flux can remain constant or grow even though there is dissipation present. There does, of course, have to be energy supplied to the system to retain a steady state against losses. This model is not by itself complete in that it postulates the existence of suitable fluctuations in the magnetic field and plasma velocity. It can be called the kinematic dynamo since self-consistent plasma dynamics following Newton and Maxwell yet need demonstration.

Recent calculations with three-dimensional codes have been employed aiming to delineate self-consistent dynamo action involving reconnection and turbulent processes. A sample of such calculations of the reconnecting surfaces of an RFP configuration are shown in Fig. 11 [Carreras, Nebel, and Schnack, 1983]. The corresponding flow is shown in Fig. 12.

The sequence of events displayed in Fig. 11 is as follows: (1) a resistively unstable RFP configuration is produced by the ohmic heating which overpeaks the current on the interior of the plasma column; (2) a first reconnection occurs which leads to a helically deformed state; (3) a second reconnection occurs which increases the magnetic shear leading to a stable configuration; (4) ohmic heating can then distort the current profile and the whole process repeats. The first reconnection is of the rapid Sweet-Parker type scaling as $\eta^{1/2}$ and described by the Kadomsev [1975] model. The second reconnection scales as η and proceeds on the slower diffusion time scale. This is in contrast to the single type of rapid reconnection returning the plasma to axisymmetry used in tokamak descriptions. The above calculations suggest a periodic "sawtooth" behavior not unlike that which has been observed on ZT-40M when operated at high Θ values [Watt and Nebel, 1983; Nebel, 1983]. These sawtooth events produce positive increments in the toroidal flux and are identified with individual "dynamo" events. Analogous events are apparent on the flux trace for a slow current rise (Fig. 9). It is noted that the above calculations are in contrast to the model of Hutchinson [1982] that uses reconnection arguments for the RFP based on the Kadomsev model for the entire process.

4.3. Helical Ohmic States

The possibility of steady state RFP having a helically symmetric plasma column with a steady plasma flow pattern and satisfying Ohm's law was suggested by the computer calculations Sykes and Wesson, [1975]. The conditions for such a state were explored by Gimblett [1980].

Preliminary studies of the problem of whether it is possible to set up a stationary ohmic helical state by the reconnection associated with the resistive tearing mode has been made [Dagazian 1980a, 1980b]. Numerical and analytic work on this problem have been reported [Schnack, 1980; Dobrott and Schnack, 1983; Aydemir and Barnes, 1983a, 1983b]. The last authors report that 2-D and 3-D computer calculations have demonstrated steady states which are maintained against resistive diffusion by the dynamo action of large helical flows.

4.4. Models With Islands and/or Stochasticity of the Magnetic Fields

An important topic is the possible breaking up of the nested flux surfaces of a toroidal equilibrium by magnetic field perturbations. It is known that rather small non-axisymmetric field errors can resonate with the helical field lines leading to a change in the field topology [Kerst, 1962]. These errors can produce small "islands" of nested surfaces, each with its own magnetic axis. As the field perturbations are made larger, portions of the error fields with different harmonic content can interact with the main fields and with each other to produce a region where there are no well-behaved flux surfaces and the field lines wander chaotically [Rosenbluth, et al., 1966; Walker and Ford, 1969; and Spencer, 1980]. Such behavior is of much interest in the fusion field because of the effects of such behavior on plasma containment. Internal plasma perturbations and reconnection processes can lead such "egodic" behavior as has been observed in 3-D computer modeling [Schnack, et al., 1983; Aydemir 1983a]. The effect of such changes in field topology on transport and plasma containment is an active area of research.

A tangled discharge model to explain the self-reversal and sustainment of an RFP has been advanced [Rusbridge, 1977; Miller, 1983]. This model retains Ohm's law but assumes that the field lines behave stochastically over the entire plasma volume. EMF's on the interior set up electrostatic fields to drive the current along the $\underline{B}$ line against the applied electric field in the reversed magnetic field region.

The possible generation of magnetic islands by reconnection in an RFP has led to a model for sustaining the configuration [Jacobson, 1984a]. The model makes use of the change in magnetic surfaces behavior produced by a periodic radial perturbing field, and the space charge electric field resulting from ion transport to drive the required currents. A second mechanism [Jacobson, 1983] uses a rectification process produced by modulating the electrical resistivity in the presence of recurring magnetic islands.

Very recently a model has been advanced [Jacobson and Moses, 1984b] which proposes RFP sustainment by replacing Ohm's law with a kinetic theory making use of a Fokker-Plank equation. The collision term is modified with a term used to describe transport in an assumed stochastic field [Rosenbluth and Rechester, 1978].

4.5. RFP Sustainment With Oscillating Fields

Even though the sustainment of the RFP configuration against dissipative field diffusion appears no longer to be a problem, there is the fact that present toroidal RFPs use an inductive toroidal electric field to maintain them. Since this field is produced by the transformer action associated with continuously increasing the flux in the central hole of the torus, this method of necessity limits the duration of the unidirectional toroidal current because the magnetic field cannot be increased indefinitely. The tokamaks share this property and schemes for driving a direct current indefinitely with a radio frequency field or particle beams have been devised and tested. Thanks to the plasma relaxation through field line reconnection processes, the RFP has a potential scheme for a steady state current drive which utilizes ac modulation of the currents on the toroidal and poloidal field windings using economical audio frequencies. This method was suggested by [Bevir and Grey, 1980]. The possibility arises from the fact that the rapid relaxation of the discharge keeps the configuration on an F-Θ trajectory as discussed in Sec. 3.2. This constitutes a nonlinear coupling between the poloidal and toroidal field circuits. Unlike a linear system, this nonlinear coupling allows the generation of a dc component of toroidal current to sustain the discharge when the proper phasing of ac modulating currents are applied to each set of field windings (see Fig. 13).

Computer calculations using a model based on the F-Θ coupling [Johnston, 1981; Schoenberg, et al., 1982] predicts the sustaining of the toroidal current by this technique [Schoenberg, et al., 1983a]. The results of such a calculation showing a steady dc component of current and constant mean-field flux are shown in Fig. 14. Preliminary experiments in which each winding of the ZT-40M experiment was individually ac modulated have confirmed the main premises on which this technique is based [Schoenberg, 1983b]. The full test to produce a net dc current by this technique on ZT-40M is planned.

5. Conclusion

It is impressive how much of the present-day RFP concepts and experiments are intimately related to the rapid field line reconnection processes. The startup, sustainment and containment are vitally controlled and modified by the relaxation of the plasma configuration through the field line reconnection phenomenon. Two areas are particularly outstanding examples where concepts having origins in the astrophysics area have greatly enhanced the laboratory study of the RFP; namely the mean-field dynamo and the plasma relaxation to a lowest energy state.

The phenomenon of reconnection in a conducting plasma leads to an area rich in mechanisms for flux generation and RFP sustainment in the presence of collisional dissipation. As further work clarifies which of the many possible mechanisms can be made self-consistent and in agreement with experimental observations, the results will have considerable impact to both the space and laboratory physics communities. It is clear that further and closer collaboration between researchers of space and astrophysics plasmas and those associated with laboratory-produced plasmas would greatly benefit both disciplines. It is hoped that this review with its extensive bibliography will aid in motivating this cooperation.

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FIGURE CAPTIONS

Fig. 1. Drawing of the Los Alamos ZT-40M reversed field pinch experiment.

Fig. 2. Schematic showing the toroidal field winding, the slotted conducting shell, and the highly-sheared field lines lying on nested flux surfaces of a reversed field pinch.

Fig. 3. Comparison of tokamak and the reversed field pinch fields. The poloidal B_θ and toroidal B_ϕ field components along the midplane of the torus are shown.

Fig. 4. Top view of a toroidal pinch inside a flux conserving shell. (a) pinched plasma and a sample field line; (b) plasma column kinked into a helix, strengthening $\underline{B}$ near the minor axis and reversing $\underline{B}$ outside.

Fig. 5. Demonstration of self-reversal of the magnetic field by plasma kinking and field merging. (a) pinched plasma; (b) pinch after kinking into a helix; separatrices and x-points have formed; (c) plasma column with reversed field configuration after field line reconnection and return to symmetry.

Fig. 6. Left: Bessel function field profiles for the Taylor lowest energy state. Right: F-Θ diagram showing field reversal for $\Theta \geq 1.2$ and the threshold for the formation of helical lowest energy states at $\Theta = 1.55$.

Fig. 7. A comparison of an experimental F-Θ trajectory obtained from a single discharge in the ZT-40M experiment with the Taylor prediction. The trajectory starts at $F = 1$ and moves to higher Θ and lower F values as the discharge current increases and the reversed field state is formed.

Fig. 8. A schematic cross section of the ZT-40M discharge showing the positive and negative flux regions and the location of the flux loop that measures the net toroidal flux inside the resistive vacuum liner.

Fig. 9. Waveforms for a slowly-rising current in ZT-40M. (a) toroidal current; (b) toroidal flux; (c) toroidal field just outside the vacuum liner.

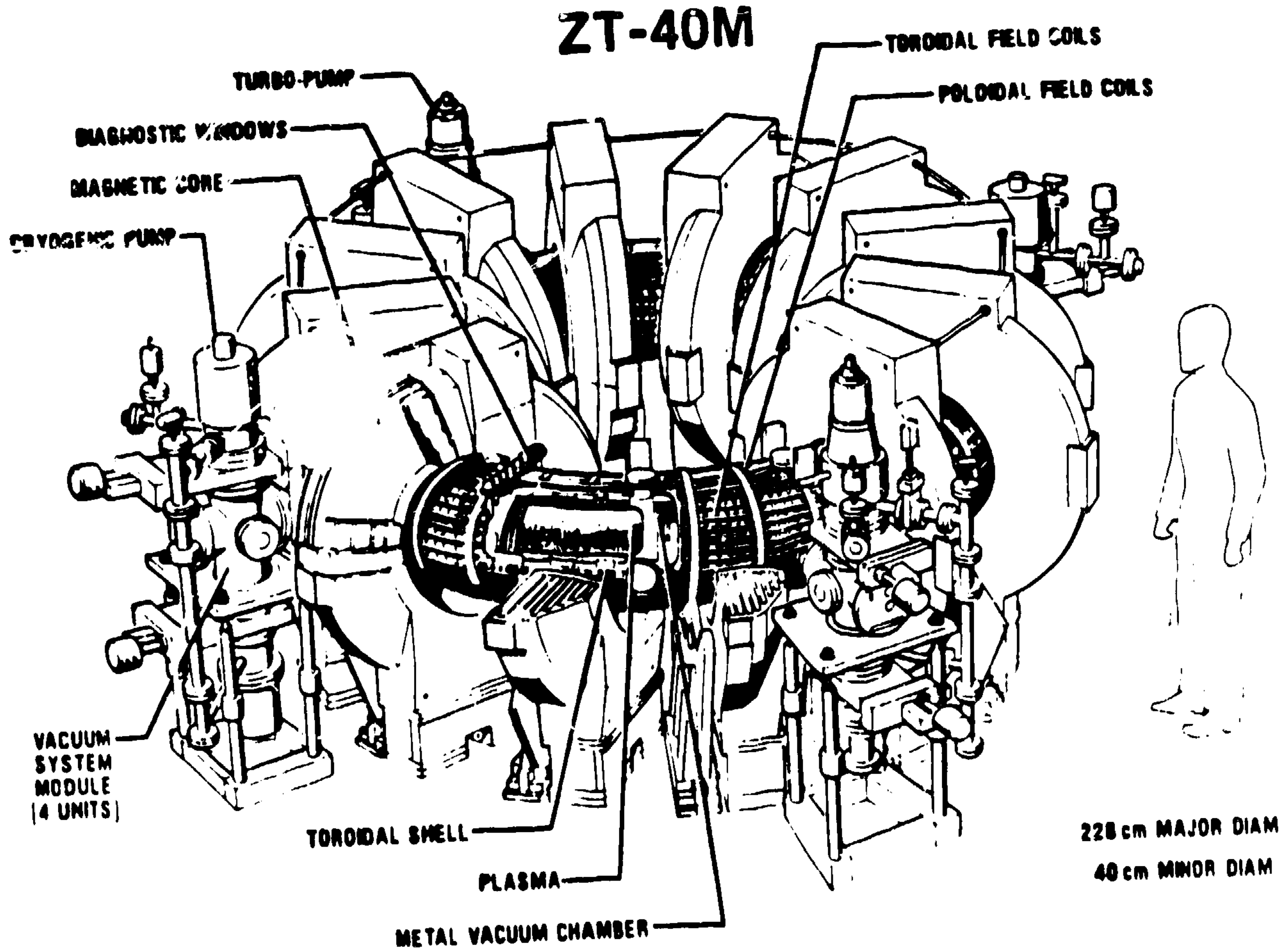
Fig. 10. Toroidal current I_ϕ, average toroidal field $\langle B_\phi \rangle$ (flux/cross-section area), external toroidal magnetic field $B_{\theta w}$ and toroidal voltage V for a long lived ZT-40M discharge.

Fig. 11. Results of a computer calculation showing the cross section of a helically symmetric magnetic surface showing a two successive reconnections.

Fig. 12. Plasma flow patterns corresponding to Fig. 11.

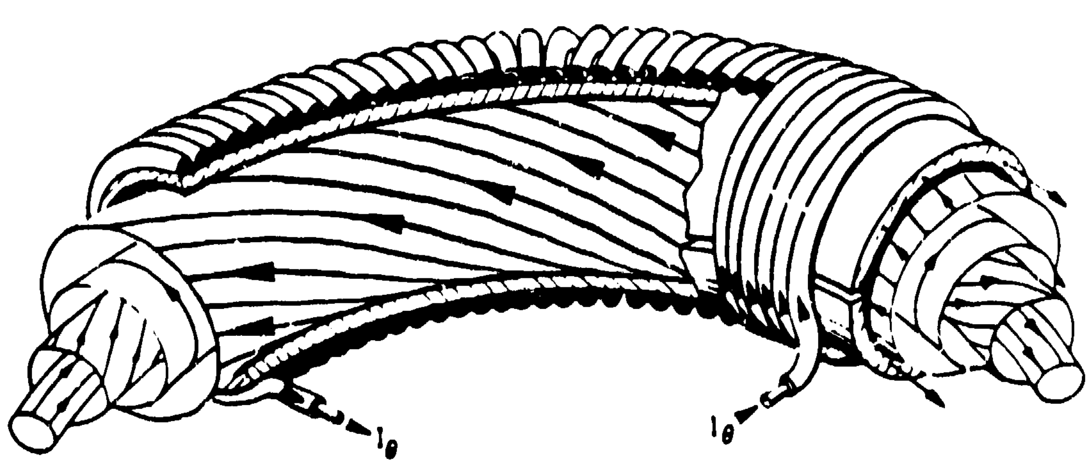
Fig. 13. Schematic showing the connection of ac voltage sources to produce a steady state dc component current in the RFP.

Fig. 14. Computer demonstration of dc current drive by driving ac voltages on the field windings. (a) current; (b) poloidal flux through the hole in the torus.



Los Alamos

FIG. 1



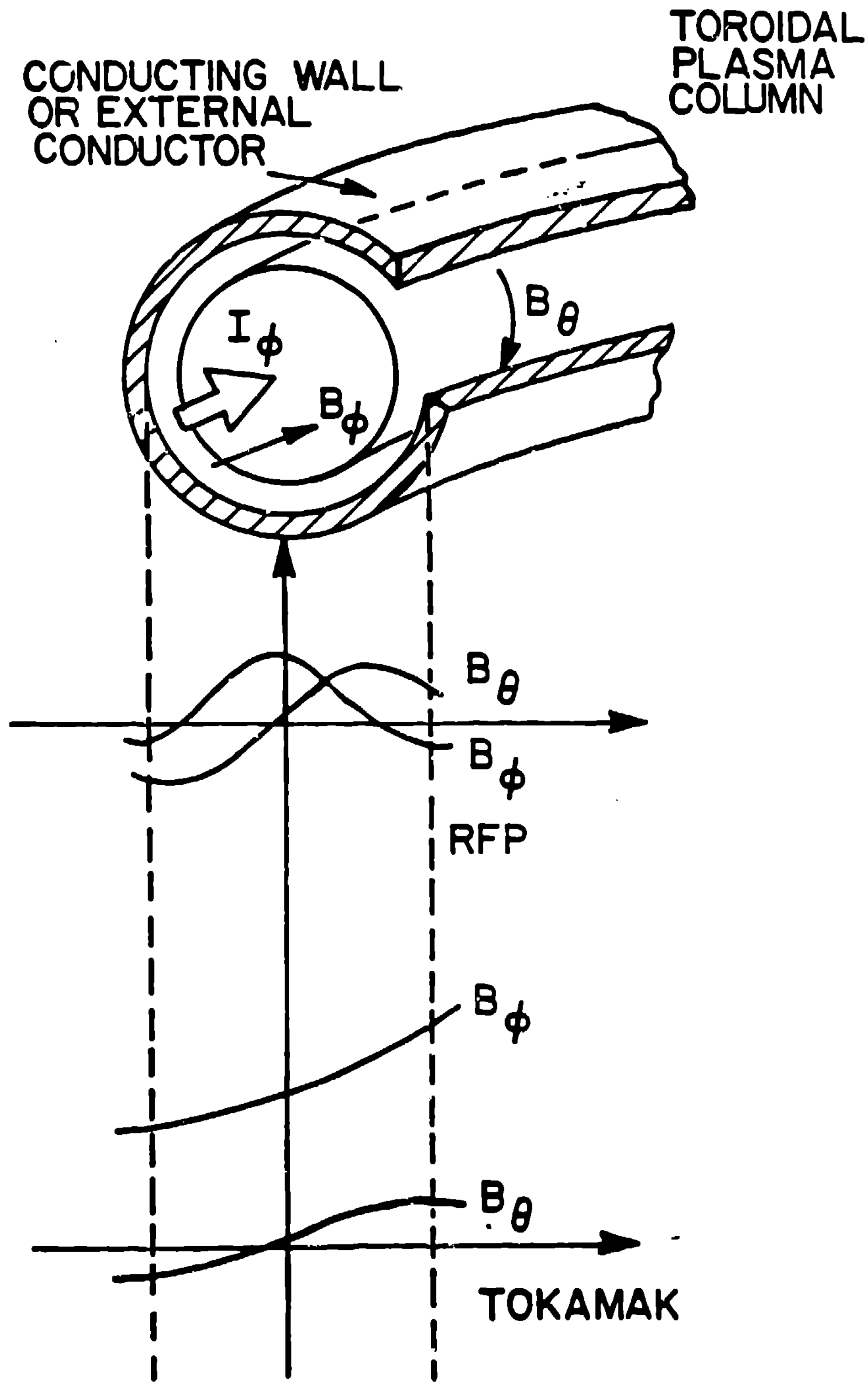
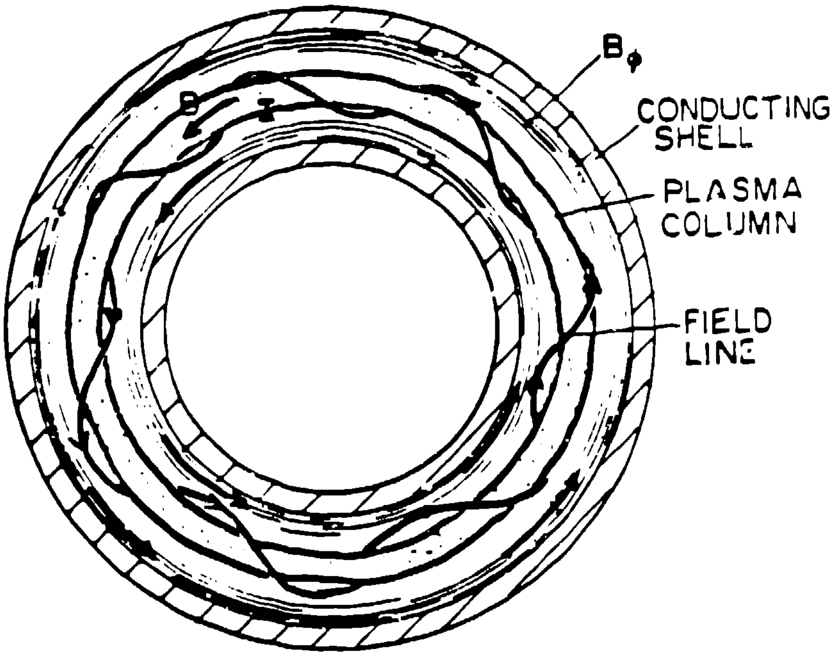

TOROIDAL
PLASMA
COLUMN
CONDUCTING WALL
OR EXTERNAL
CONDUCTOR
B_θ
I_ϕ
B_ϕ
B_θ
B_ϕ
RFP
B_ϕ
B_θ
TOKAMAK

FIG. 3

(a)


B
I
B_ϕ
CONDUCTING
SHELL
PLASMA
COLUMN
FIELD
LINE

(b)

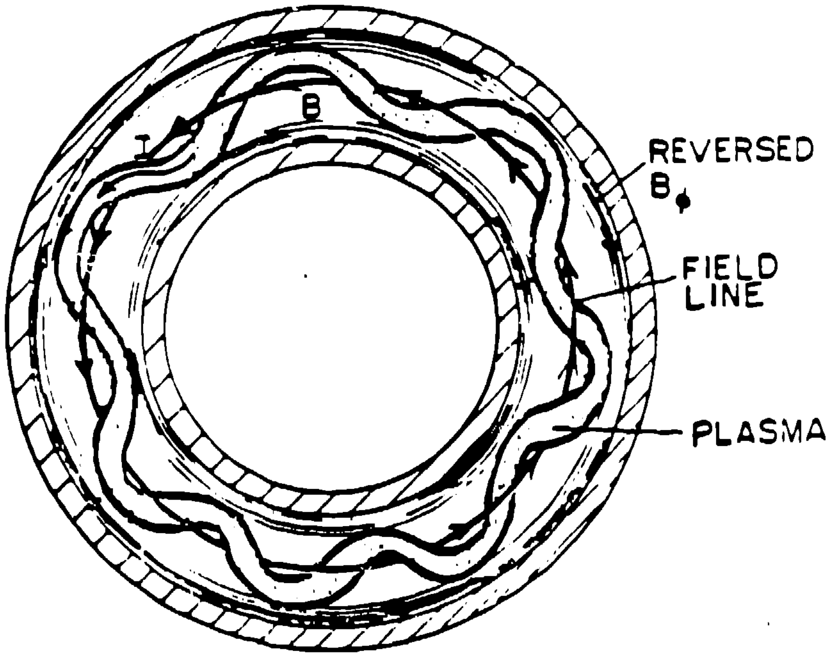

B
I
REVERSED
B_ϕ
FIELD
LINE
PLASMA

FIG. 4

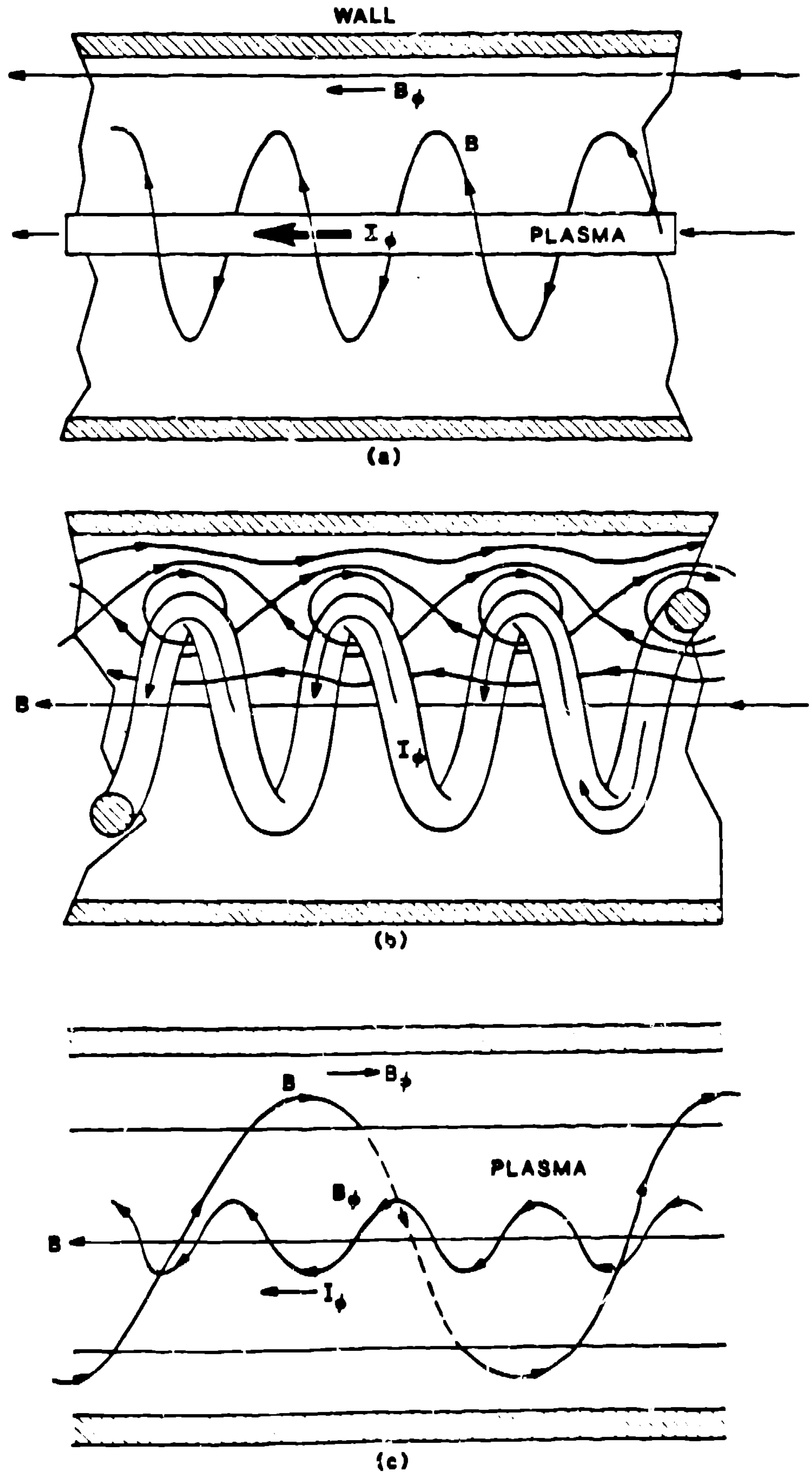
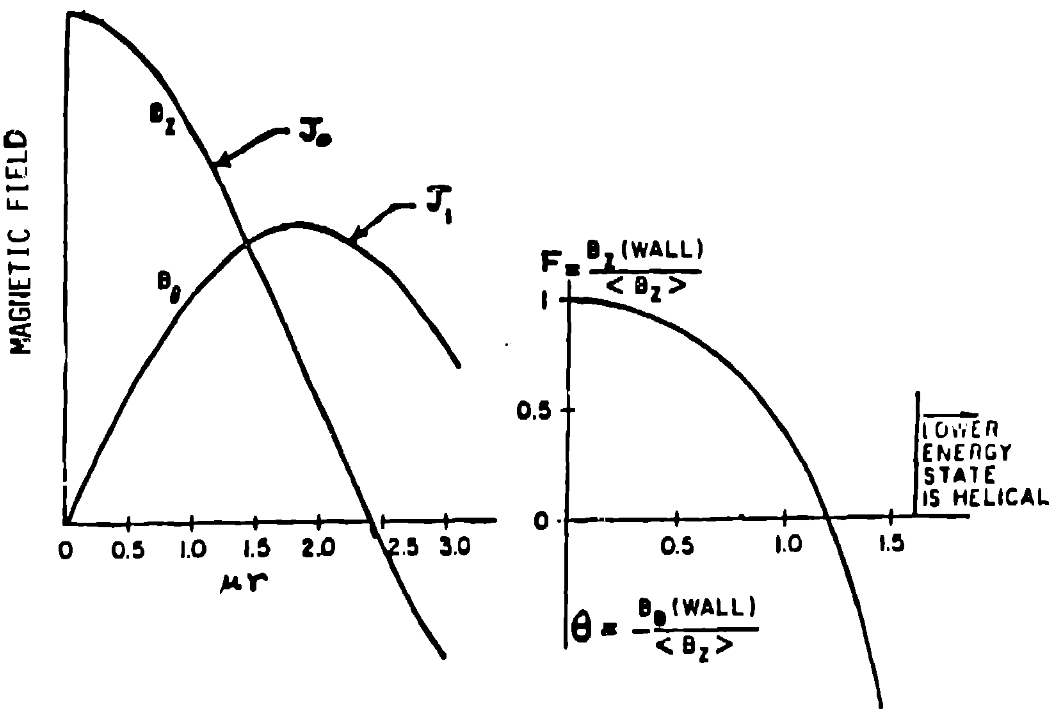
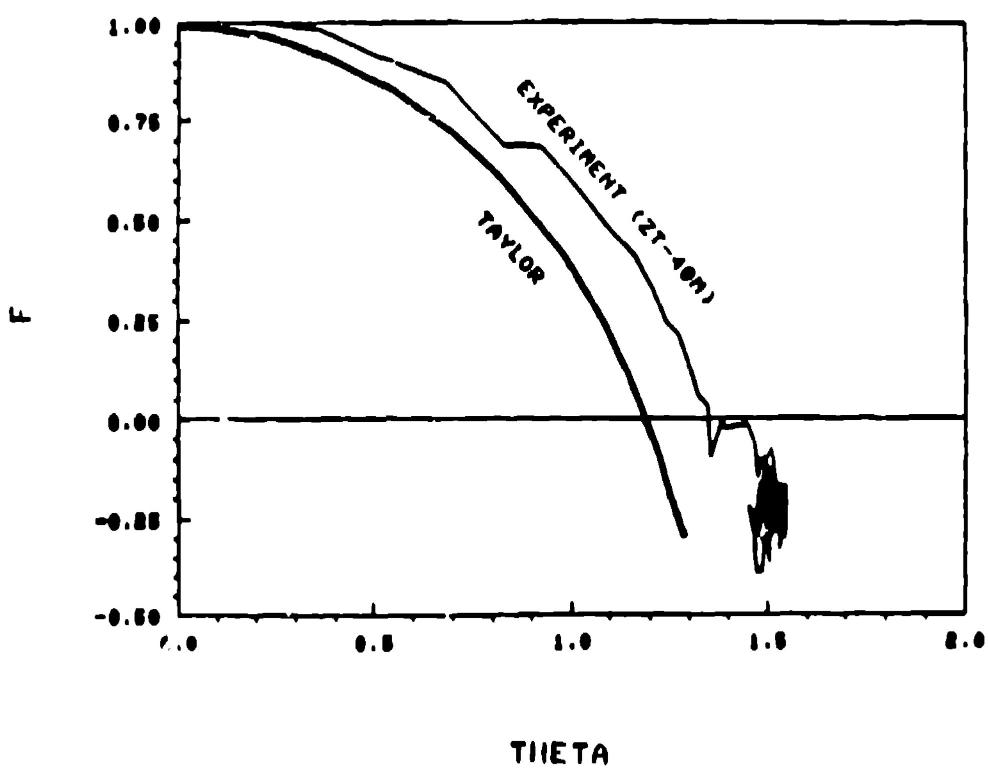


FIG. 5



MAGNETIC FIELD
B_z
J_0
J_1
B_θ
μr
0 0.5 1.0 1.5 2.0 2.5 3.0
$F = \frac{B_z\,(WALL)}{\langle B_z \rangle}$
1
0.5
0
0.5 1.0 1.5
LOWER ENERGY STATE IS HELICAL
$\theta = \frac{B_\theta\,(WALL)}{\langle B_z \rangle}$

FIG. 6



EXPERIMENT (ZT-40M)
TAYLOR
F
1.00
0.75
0.50
0.25
0.00
-0.25
-0.50
0.5
1.0
2.0
THETA

FIG. 7

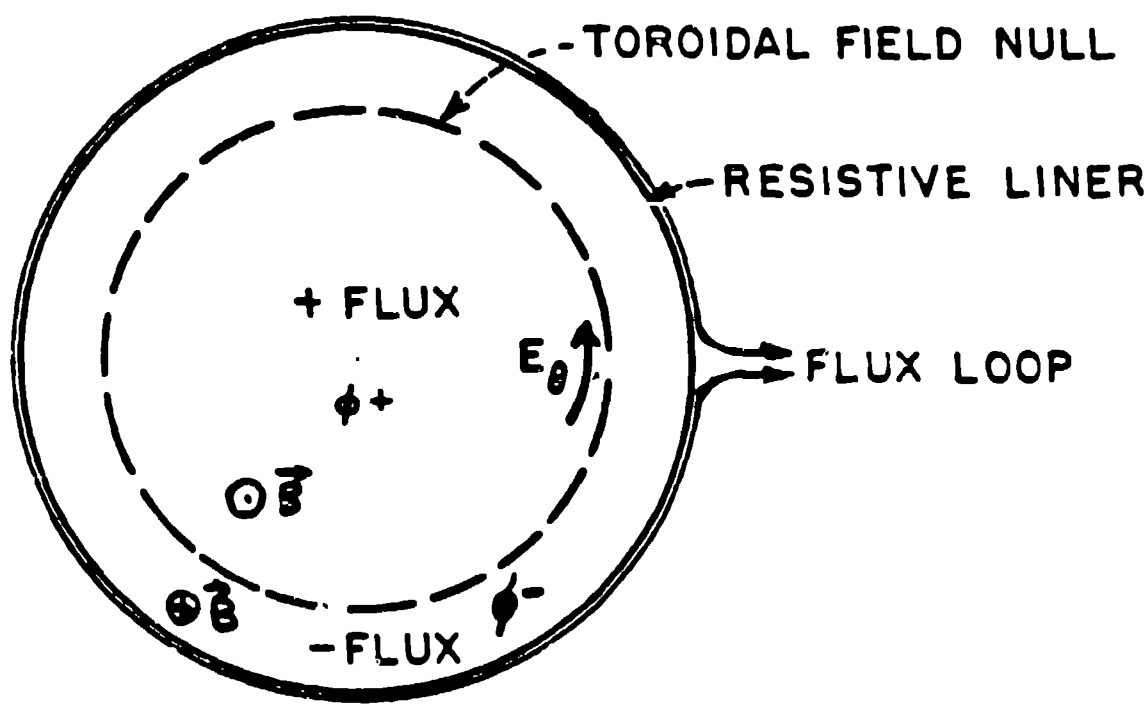
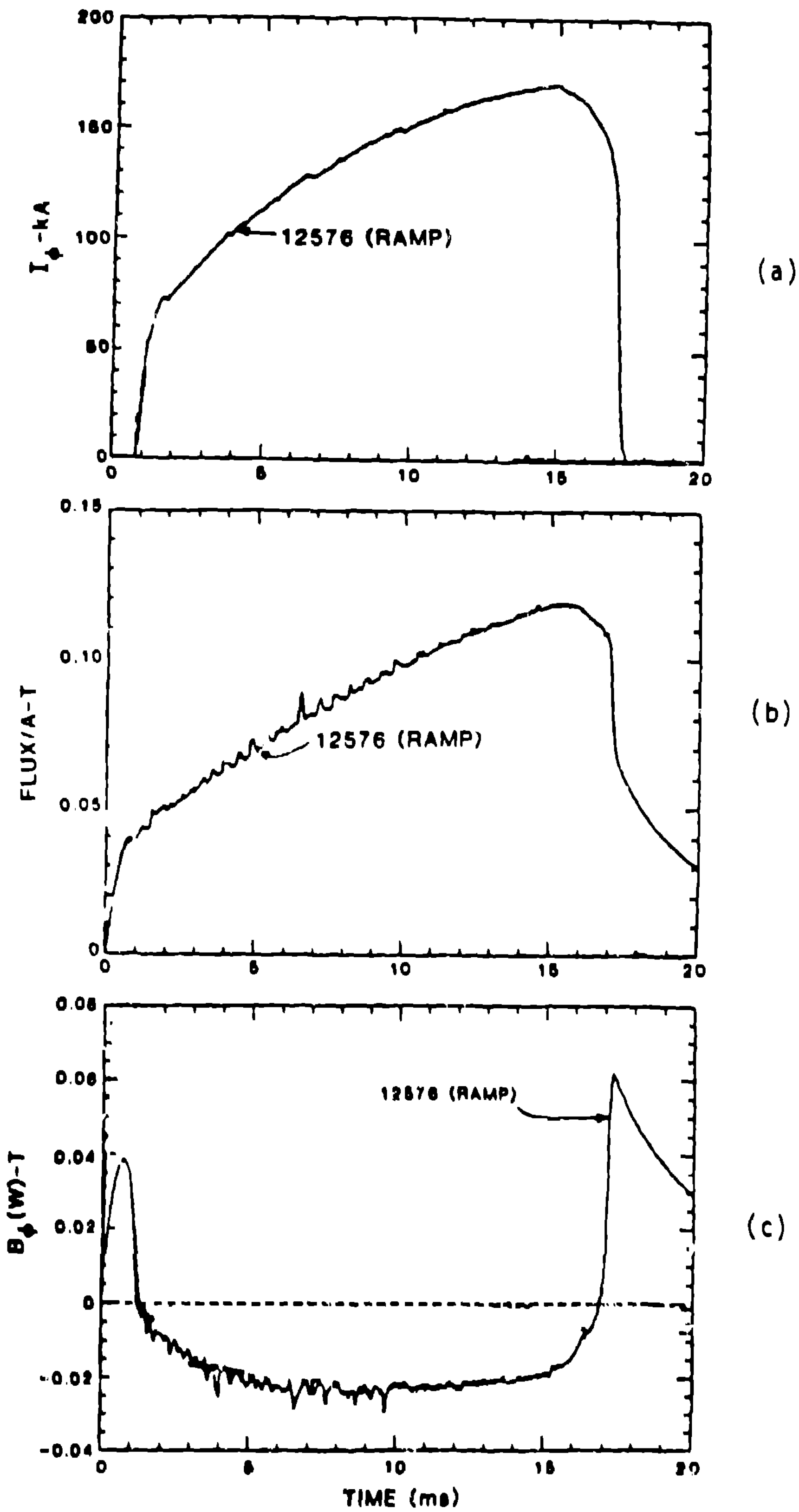
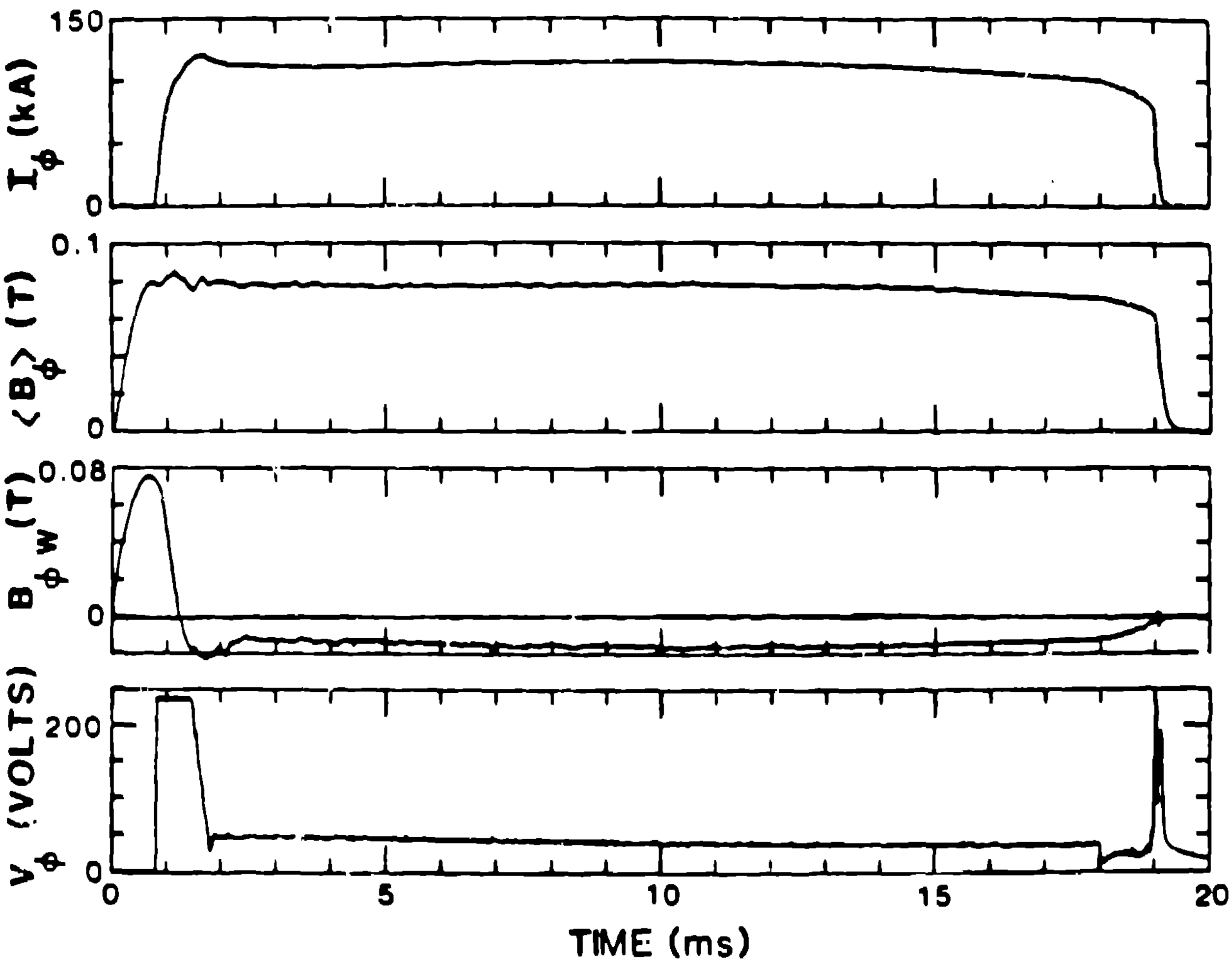

TOROIDAL FIELD NULL
RESISTIVE LINER
+ FLUX
E_θ
FLUX LOOP
ϕ+
$\odot\vec{B}$
$\otimes\vec{B}$
ϕ-
-FLUX

FIG. 8



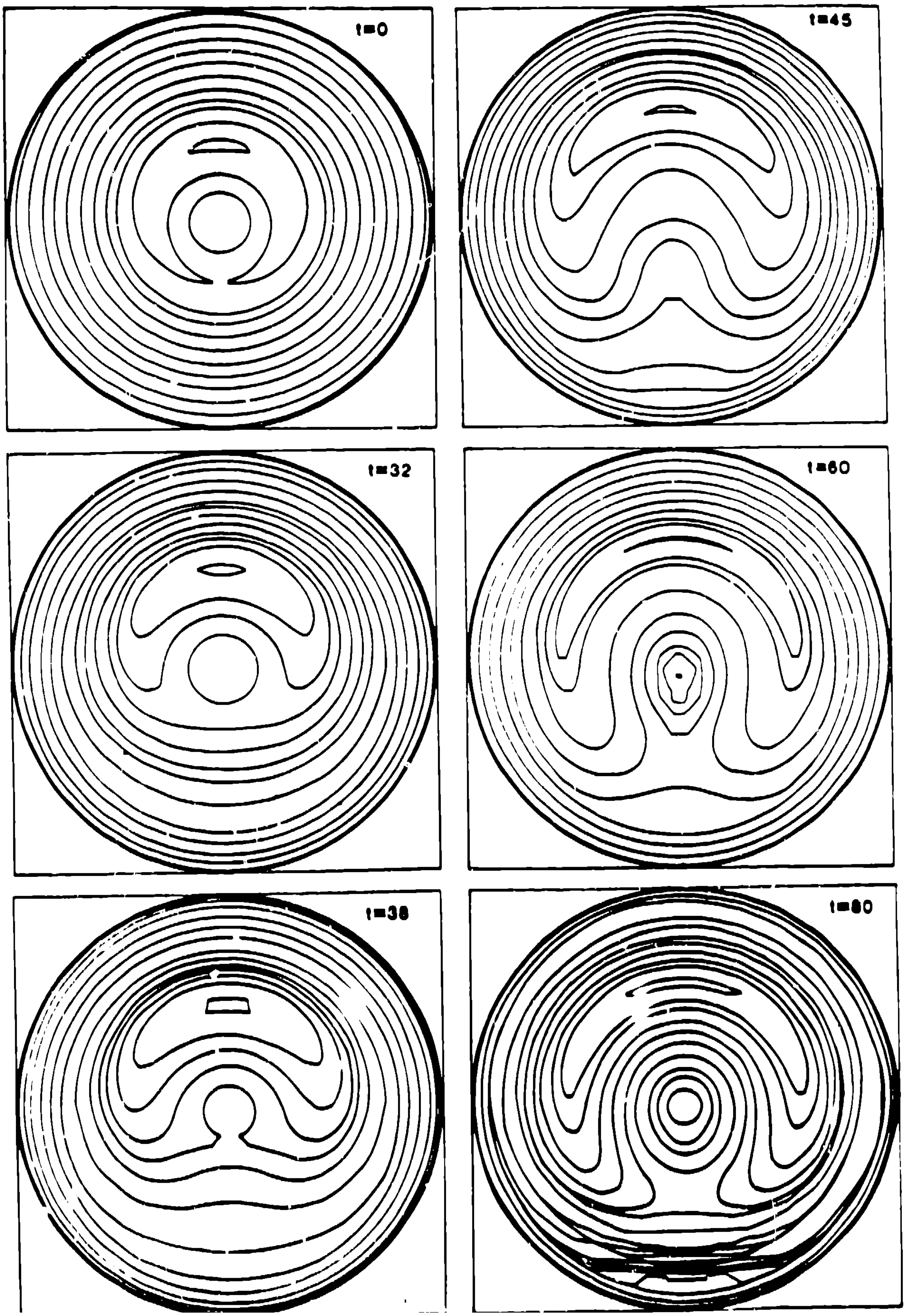
200
150
100
50
0
I_ϕ-kA
12576 (RAMP)
0
5
10
15
20
(a)
0.15
0.10
0.05
0
FLUX/A-T
12576 (RAMP)
0
5
10
15
20
(b)
0.08
0.06
0.04
0.02
0
-0.02
-0.04
B_ϕ(W)-T
12576 (RAMP)
0
5
10
15
20
TIME (ms)
(c)

FIG. 9



150
0
I_ϕ (kA)
0.1
0
$\langle B_\phi \rangle$ (T)
0.08
0
$B_{\phi w}$ (T)
200
0
V_ϕ (VOLTS)
0
5
10
15
20
TIME (ms)

FIG. 10



t=0
t=45
t=32
t=60
t=38
t=80

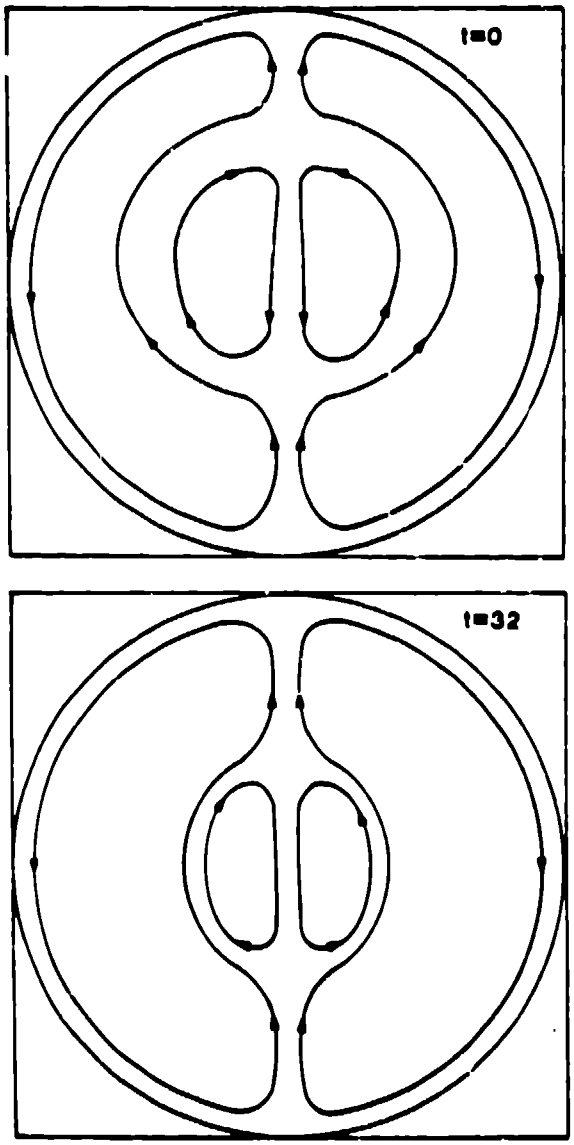


FIG. 12

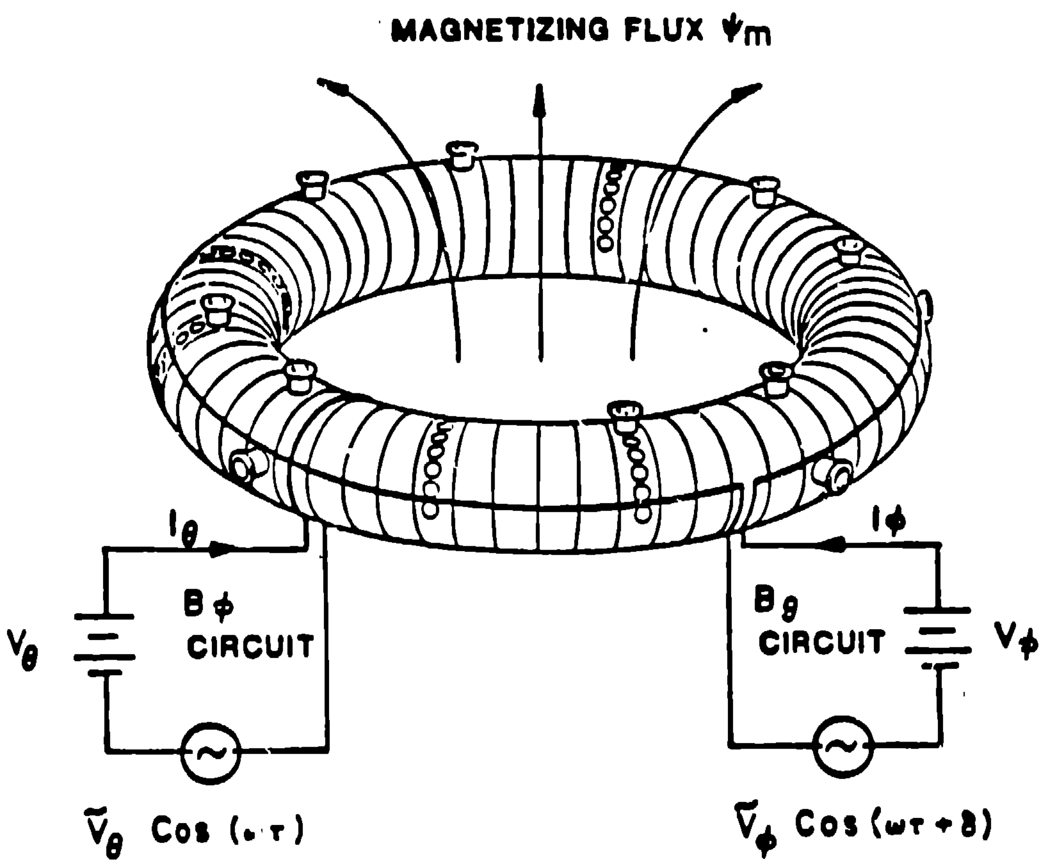

MAGNETIZING FLUX ψ_m
I_θ
I_ϕ
B_ϕ
CIRCUIT
B_θ
CIRCUIT
V_θ
V_ϕ
$\tilde{V}_\theta$ Cos $(\omega\tau)$
$\tilde{V}_\phi$ Cos $(\omega\tau + \delta)$

FIG. 13

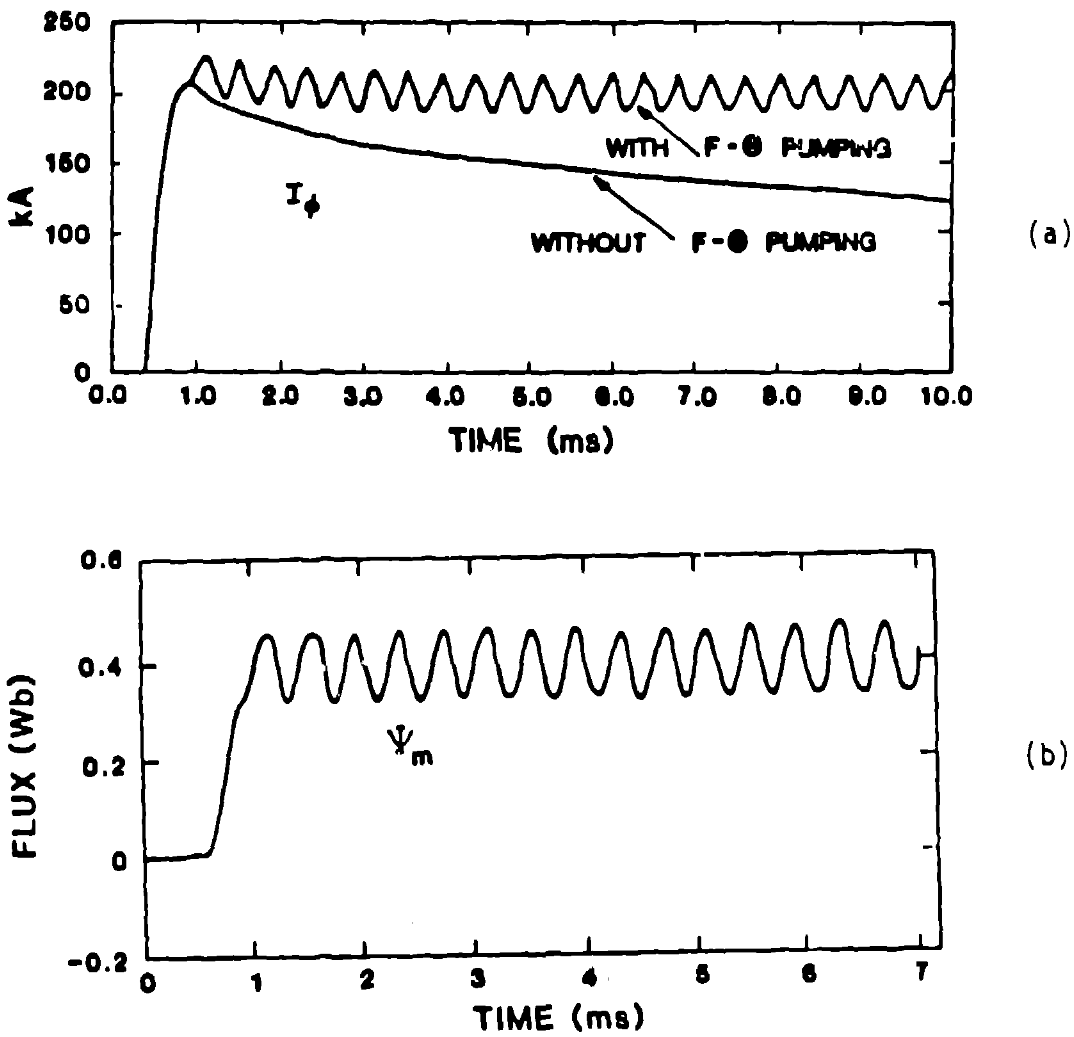

250
200
150
100
50
0
kA
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
TIME (ms)
WITH F-Θ PUMPING
WITHOUT F-Θ PUMPING
I_ϕ
(a)
0.6
0.4
0.2
0
-0.2
FLUX (Wb)
0
1
2
3
4
5
6
7
TIME (ms)
Ψ_m
(b)

FIG. 14